Chapter 10

EVOLUTION OF THE INDO-PACIFIC WARM POOL AND HADLEY-WALKER CIRCULATION SINCE THE LAST DEGLACIATION

Michael K. Gagan[1] and Lonnie G. Thompson[2]
[1]*Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia*
[2]*Department of Geological Sciences and Byrd Polar Research Center, The Ohio State University, 108 Scott Hall, 1090 Carmack Road, Columbus, Ohio 43210-1002, U.S.A.*

Abstract

The Indo-Pacific warm pool (IPWP), East Pacific cold tongue, and deep overturning atmospheric Hadley (meridional) and Walker (zonal) circulations form a tightly coupled system. In this chapter, we explore the concept of the Hadley circulation as the fundamental driver of changes in this system, and examine its possible impact on global climates of the past. Recent modeling studies indicate that the Hadley circulation is sensitive to Milankovitch forcing, dominated by the precession cycle (22,000 years) in the tropics. It is well established that the increasing Northern Hemisphere summer insolation during the post-glacial transition enhanced northern summer monsoon rainfall, particularly across the Asian landmass. Based on the results of modeling studies, it is probable that the northward asymmetry in tropical heating led to asymmetrical intensification of the Hadley circulation during the early Holocene.

The response of the tropical ocean to the intensification of the Hadley circulation is given by foraminiferal Mg/Ca and coral Sr/Ca sea surface temperature (SST) reconstructions, which show that ocean-atmosphere feedbacks drove the tropical Pacific into a westward-concentrated La Niña–like state (warming in the west, cooling in the east) between ~11,000 and ~4,000 years ago. At the same time, air temperatures reconstructed from Southern Hemisphere high-altitude tropical ice cores also equal or exceed late Holocene values. The widespread warming of the tropical middle troposphere during the early Holocene suggests that the additional flux of water vapor and heat from the warmer IPWP during the La Niña state overwhelmed any atmospheric cooling brought about by the expansion of the East Pacific cold tongue. However, the expanded cold tongue area could also play a role in the early Holocene warming through enhanced

H.F. Diaz and R.S. Bradley (eds.), The Hadley Circulation: Present, Past and Future, 289–312.

evasion of CO_2 to the atmosphere.

Taken together, the paleoclimate records indicate that a post-glacial strengthening of the Hadley circulation initiated ocean-atmosphere feedbacks that altered the energy budget of the tropics to amplify early Holocene warming. Synchronous warming of the Southern Hemisphere high latitudes, as indicated by Antarctic ice core records, may be the result of southward-directed dynamical heating produced by the asymmetrical Hadley circulation. The demise of the early Holocene warming in the tropics and Southern Hemisphere ~4,000 through 7,000 years ago correlates with decreasing Northern Hemisphere summer insolation, a southward migration of the Intertropical Convergence Zone (ITCZ), and the onset of modern El Niño/Southern Oscillation (ENSO) variability.

1. INTRODUCTION

The Hadley circulation is the large-scale tropical atmospheric circulation consisting of a deep overturning meridional circulation cell where regions of ascending air, near the thermal equator, are connected to subsiding branches over the subtropics (Pierrehumbert 2000). Energy associated with the equatorial maximum in solar radiation released through vigorous atmospheric convection is the ultimate driver of the mean position of the Hadley circulation (Lindzen and Hou 1988; Hou 1998; Rind 1998). In terms of the coupled ocean-atmosphere system, the Hadley circulation can be viewed as the fundamental driver of the western warm pool – eastern cold tongue configuration in sea surface temperature (SST) that is particularly prominent in the tropical Pacific Ocean (Liu and Huang 1997; Liu 1998). Surface winds converging toward the thermal equator in the lower limbs of the Hadley circulation are deflected westward by the Coriolis force. The resulting easterly trade winds drive equatorial upwelling, a cold tongue in the east, and the westward accumulation of advected warm water in the Indo-Pacific warm pool (IPWP), where average annual SSTs exceed 28°C (Fig. 10-1; Yan et al. 1992).

The zonal Walker circulation embedded in the Hadley circulation owes its origin to the cold tongue – warm pool gradient in SSTs across the Pacific Ocean. This is because deep atmospheric convection above the IPWP concentrates thermal energy in the ascending limb of Indo-Pacific section of the Hadley circulation (Bjerknes 1966), whereas the air above the cold tongue in the east makes a relatively minor contribution. Thus, relatively cool air flows westward in the lower limb of the Walker circulation where it becomes moistened and heated, and rises through deep convection above the IPWP to reinforce the Hadley circulation. This concept of the Hadley circulation as a fundamental driver of a tightly coupled Pacific cold tongue, warm pool, and Walker circulation system may apply since the final closure of the Isthmus of Panama and the establishment of thermal gradients across the Pacific about 3 million years ago (Keigwin 1978; Romine 1982; Philander and Federov 2003).

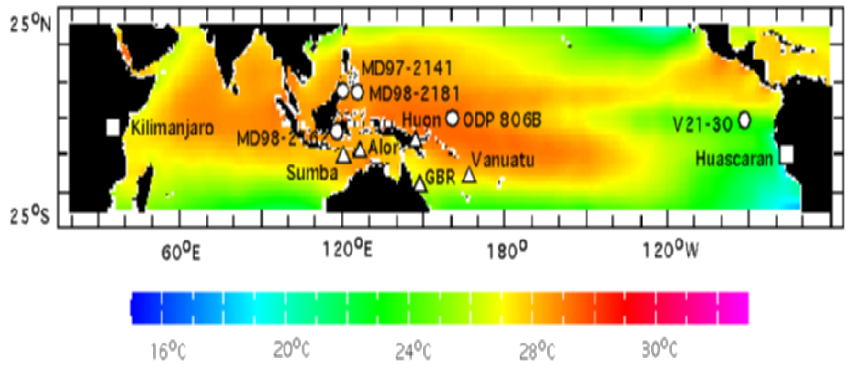

Figure 10-1. Locations of deep-sea sediment cores (circles), corals (triangles), and tropical ice core (squares) paleoclimate records described in Figures 10-2 through 10-5. Red shows the average extent of the Indo-Pacific warm pool (mean annual SST > 28°C), as defined by Yan et al. (1992).

Recent modeling studies have shown that the nonlinear response of the coupled cold tongue, warm pool, Hadley-Walker circulation system to insolation fluctuations, dominated by the precession cycle (22,000 years) in the tropics, may be sufficient to yield substantial millennial-scale climate variability (Cane and Clement 1999; Clement et al. 2001). The IPWP is a good candidate for driving this variability because changes in its temperature, size, and positioning can alter atmospheric circulation at higher latitudes (Barlow et al. 2002; Chen et al. 2002; Hoerling and Kumar 2003). Hou (1993) showed that displacements of the tropical heating maximum are reflected in changes in the winter polar temperature, and relatedly, in the heat flux between the tropics and the polar regions. The resulting changes in heat flux lead to changes in the mean temperature of the earth, even though there is no change in the globally averaged insolation. The implication is that Milankovitch variations in the seasonal distribution of insolation could have a profound effect on global climate (Lindzen and Pan 1994). Therefore, a crucial issue in global climate change research is to reconstruct tropical SSTs and the locus of atmospheric convection in the tropics.

Recently, tandem measurements of Mg/Ca and $\delta^{18}O$ in planktonic foraminifera have been used to reconstruct changes in the temperature and $\delta^{18}O$ of surface seawater over glacial-interglacial time scales, and make inferences about the surface-ocean water balance in the tropics (Lea et al. 2000; Kienast et al. 2001; Koutavas et al. 2002; Stott et al. 2002; Rosenthal et al. 2003; Visser et al. 2003). These records reveal millennial-scale changes in the tropical Pacific ocean/atmosphere system analogous to the El Niño/Southern Oscillation (ENSO), whereby El Niño–like conditions in the IPWP region (cooler/drier) correlate with stadials at high latitudes and La Niña–like conditions (warmer/wetter) correlate with interstadials (Koutavas et al. 2002; Stott et al. 2002). A La Niña–like state in tropical Pacific SSTs during the early Holocene implies that the Hadley-Walker circulation system was invigorated at that time. Climate models indicate that precessional forcing produced ocean-atmosphere feedbacks leading to a nonlinear climate response to changes in insolation during the Holocene (Clement et al. 2000; Liu et al. 2000). Therefore, knowledge of SST in the IPWP and its effect on the Hadley-Walker circulations during the Holocene is crucial for understanding the specific mechanisms by which subtle changes in insolation seasonality were converted to significant changes in tropical climate.

In this chapter, we review the most recent estimates of SST variability in the coupled Pacific cold tongue–IPWP system since the last glacial maximum (LGM). We then examine the oxygen isotopic signals recorded by high-altitude tropical ice cores over the same period to investigate interactions between tropical SSTs and the tropical troposphere. Comparisons with air temperature records reconstructed from polar ice cores provide evidence for the potential role of the coupled Pacific cold tongue–IPWP–Hadley/Walker circulation system in global climate change. Data-model comparisons provide insight into the ocean-atmosphere interactions driving post-glacial climate change. Finally, we discuss possible analogies with future climate change.

2. POST-GLACIAL EVOLUTION OF THE PACIFIC COLD TONGUE AND IPWP

Two promising new paleothermometers, Mg/Ca in surface-dwelling foraminifera and Sr/Ca in corals, have led to important findings about the temperature history of the IPWP since the LGM. Studies of foraminiferal Mg/Ca from deep-sea sediment cores provide long, continuous histories of changes in mean SST (Lea et al. 2000; Kienast et al. 2001; Koutavas et al. 2002; Stott et al. 2002; Rosenthal et al. 2003; Visser et al. 2003). Corals from the tropical Pacific provide complementary high-resolution records of Holocene climate change at monthly or better temporal resolution (Beck et al. 1992, 1997; McCulloch et al. 1996; Gagan et al. 1998; Corrège et al. 2000; Tudhope et al. 2001). Recently, these paleothermometers have been used to extract the temperature component of the oxygen isotope signal in biogenic carbonates and thereby reveal changes in seawater ^{18}O concentrations as a proxy for surface-ocean salinity (e.g., Gagan et al. 1998, 2000; Lea et al. 2000; Hendy et al. 2002; Stott et al. 2002; Rosenthal et al. 2003).

We first review the primary findings from planktonic foraminiferal Mg/Ca records from the IPWP region (Lea et al. 2000; Kienast et al. 2001; Stott et al. 2002; Rosenthal et al. 2003; Visser et al. 2003) and the East Pacific cold tongue (Koutavas et al. 2002). We then present revised temperature estimates for the IPWP region, based on coral Sr/Ca ratios, including data sets from Vanuatu (Beck et al., 1992, 1997; Corrège et al. 2000), Papua New Guinea (McCulloch et al. 1996), the Great Barrier Reef (Gagan et al. 1998), and eastern Indonesia (Gagan et al. 2004).

Paleotemperature estimates for the IPWP region derived from Mg/Ca in *Globigerinoides ruber* in the IPWP region show cooling of 2°C–4°C during the LGM (Lea et al. 2000; Stott et al. 2002; Rosenthal et al. 2003; Visser et al. 2003). In contrast, the East Pacific cold tongue exhibits a much smaller cooling of ~1°C (Koutavas et al. 2002). Comparisons of Mg/Ca and $\delta^{18}O$ measured in the same foraminifers indicates that the rise in IPWP SSTs led deglaciation by ~3,000 years (Lea et al. 2000; Stott et al. 2002; Visser et al. 2003). Interestingly, all the records show a rapid rise to modern SST values by the early Holocene (~11,000 BP; Fig. 10-2).

Estimating mean SST in the tropical western Pacific using coral Sr/Ca paleothermometry has been controversial because early estimates indicated cooling of 3°C–6°C during the early Holocene (Beck et al. 1992, 1997; McCulloch et al. 1996). A clearer picture emerges for the Southern Hemisphere portion of the IPWP when a single calibration equation derived specifically for application to continental and island arc fringing reefs (Gagan et al. 1998) is applied to fossil coral Sr/Ca data for Vanuatu (Beck et al.

1997; Corrège et al. 2000), Papua New Guinea (McCulloch et al. 1996), the inshore Great Barrier Reef (Gagan et al. 1998), and Sumba/Alor in southeastern Indonesia (Gagan et al. 2004). The revised Vanuatu coral SST estimates for the early Holocene now indicate cooling of 1°C–3°C, rather than 4°C–6°C. New coral Sr/Ca records from Alor, southeast Indonesia, show that SSTs reached modern values by ~8,500 BP, in good agreement with the foraminiferal Mg/Ca estimates of SST. This generally warm period is interrupted by a brief cold-spike centered on 8,100 BP. Mid-Holocene SSTs in Indonesia (Sumba) fall within 0.5°C of modern values, whereas corals from the inshore Great Barrier Reef, Australia, indicate SSTs ~1°C warmer than the present.

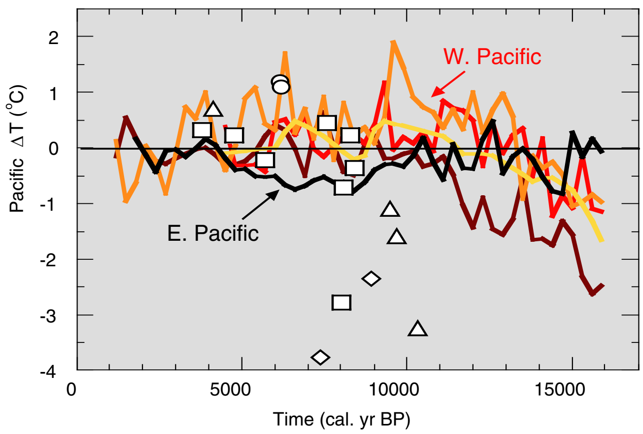

Figure 10-2. Comparison of SSTs in the equatorial eastern Pacific and IPWP regions during the last 16,000 years, as reconstructed using foraminiferal Mg/Ca and coral Sr/Ca thermometry. For the IPWP region, SST anomalies (relative to 0–5,000 BP) were reconstructed from Mg/Ca in the planktonic foraminifer *Globigerinoides ruber* from core MD98-2162 in Makassar Strait, Indonesia (4°41.33'S, 117°54.17'E; burgundy curve; Visser et al. 2003); core MD97-2141 in the Sulu Sea (8.8°N, 121.3°E; red curve; Rosenthal et al. 2003); core MD98-2181 south of the Philippines (6.3°N, 125.83°E; orange curve; Stott et al. 2002); and core ODP 806B from Ontong Java Plateau (0°19.1'N, 159°21.7'E; yellow curve; Lea et al. 2000). For the equatorial eastern Pacific, SST anomalies (relative to 1,700–4,000 BP) were reconstructed from Mg/Ca in the planktonic foraminifer *Globigerinoides sacculifer* from core V21-30 near the Galapagos Islands (1°13'S, 89°41'W; black curve; Koutavas et al. 2002). Sediment core age models are based on accelerator mass spectrometer (AMS) ^{14}C dates calibrated to calendar years before the present (cal. yr BP), and foraminiferal δ^{18}O stratigraphy. Coral Sr/Ca SST anomalies are based on fossil specimens of *Porites* from Espiritu Santo, Vanuatu (15°40'S, 167°E; triangles; Beck et al. 1997; Corrège et al. 2000); Huon Peninsula, Papua New Guinea (6°S, 147°E; diamonds; McCulloch et al. 1996); Orpheus Island, Great Barrier Reef (18°34'S, 146°29'E; circles; Gagan et al. 1998); and southern Indonesia (Alor, 8°14'S, 124°24'E; Sumba, 09°28'S, 120°06'E; squares). The relationship for converting coral Sr/Ca to SST is: T(°C) = 168.2 – [15,674*(Sr/Ca)atomic], which has been derived for modern *Porites* specimens from open-water continental and island arc fringing reefs throughout the Indo-Pacific region (Gagan et al. 1998). ^{230}Th/^{234}U calendar ages for corals were determined by thermal ionization mass spectrometry (TIMS).

Although the new coral SST estimates and foraminiferal Mg/Ca SST estimates are now in much better agreement, some of the coral records are still significantly cooler or warmer than the deep-sea sediment core estimates. Coral records showing cool SSTs could be recording real changes, particularly coastal upwelling, on time scales of decades. Cool artifacts may also be caused by early marine aragonite cements (Müller et al. 2001) and off-axis sampling of coral skeletons (de Villiers et al. 1994). Warm artifacts, on the other hand, may result from calcite diagenesis in corals sampled from uplifted coral terraces (McGregor and Gagan 2003).

The rapid late-glacial to early Holocene warming of the IPWP is consistent with a semipermanent La Niña–like state in mean SSTs (Koutavas et al. 2002; Stott et al. 2002). The La Niña state would tend to elevate the thermocline in the eastern equatorial Pacific, and deepen it in the west. Westward advection of warm water would increase surface-ocean dynamic heights in the western Pacific and increase poleward flows in western boundary currents and the export of warm water to the southeastern Indian Ocean, via the Indonesian Throughflow (Meyers 1996). Such processes would increase SSTs at Southern Hemisphere study sites such as the Great Barrier Reef, Sumba, and Alor during the early to middle Holocene, in agreement with the coral Sr/Ca SST reconstructions.

The existence of prolonged La Niña conditions with a strong focus on a warm IPWP during the early Holocene is supported by paleo-ENSO records (Fig. 10-3). The most continuous, high-resolution record of ENSO for the post-glacial and early Holocene comes from laminated clastic deposits in a high-altitude lake, Laguna Pallcacocha, in Ecuador (Rodbell et al. 1999; Moy et al. 2002). Today, these clastic laminae record anomalously high rainfall during El Niño events. However, the sedimentary record shows a clear suppression of ENSO variability, with periodicities of ~15 years, from 12,000 (the beginning of the record) to 7,000 BP.

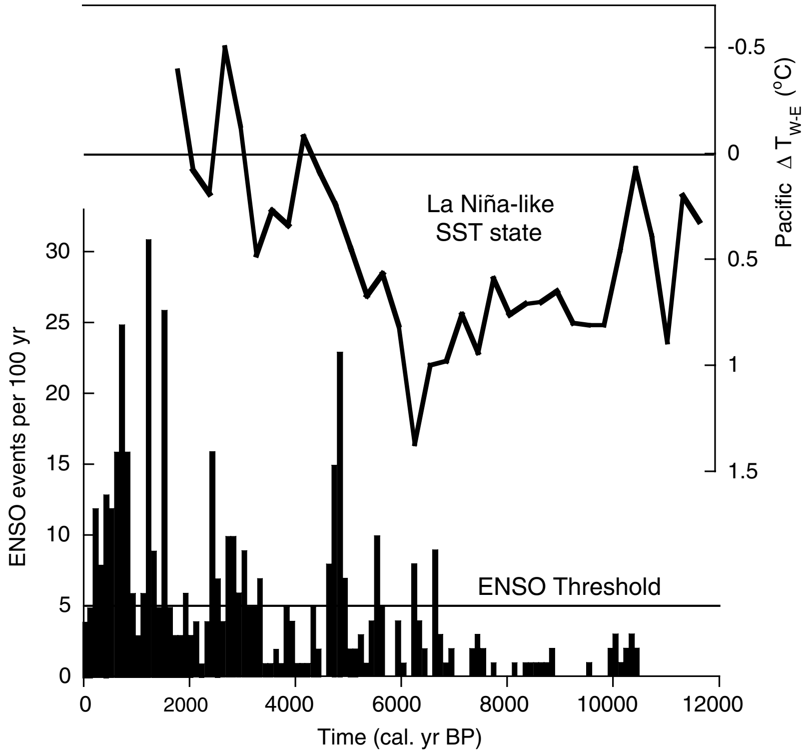

Figure 10-3. Comparison of changes in the east-west SST gradient ($\Delta T_{W\text{-}E}$) across the tropical Pacific and the frequency of moderate to strong El Niño events over the last 12,000 years. $\Delta T_{W\text{-}E}$ is the difference (relative to the late Holocene) between the mean SST given by the four foraminiferal Mg/Ca records from the IPWP and the Galapagos foraminiferal Mg/Ca SST record (shown in Fig. 10-2). Relatively warm SSTs in the IPWP (positive values downward on Y axis) indicate a La Niña–like state in Pacific SSTs. The histogram shows the number of El Niño events in 100-year windows since 12,000 BP., based on the analysis of clastic laminae in lake Laguna Pallcacocha, southern Ecuador (after Moy et al. 2002). The solid line indicates the minimum number of events (~5) required to produce ENSO-band variance.

3. POST-GLACIAL INTENSIFICATION OF THE HADLEY-WALKER CIRCULATION

The rise of tropical SSTs in advance of the change in global ice volume (Lea et al. 2000; Stott et al. 2002; Visser et al. 2003) and early Holocene SSTs similar to, or above, modern values indicate that the tropics may have played a key role in driving post-glacial global warming. Here we explore the possibility that the early Holocene intensification of the Pacific cold tongue–IPWP SST gradient and, presumably, the Hadley-Walker circulation, initiated feedbacks that altered the energy budget of the planet to amplify post-glacial warming. It is well established that, in addition to initiating the melting of the Northern Hemisphere ice caps, the increasing Northern Hemisphere summer insolation also enhanced summer monsoon rainfall across the Asian landmass, particularly during the early Holocene (see review by Morrill et al. 2003). Our hypothesis is that this asymmetry in tropical heating also enhanced the Hadley circulation and synchronously warmed the Southern Hemisphere high latitudes via dynamical heating mechanisms (Hou 1993, 1998; Lindzen and Pan 1994). The resulting La Niña–type configuration in zonal SSTs across the Pacific could then have altered the atmospheric greenhouse effect through increased emission of CO_2 from the expanded cold tongue region, and enhanced water vapor evaporated from the warmer IPWP.

High-altitude tropical ice core records should be particularly sensitive to changes in tropical Pacific SSTs and evaporation in the IPWP region considering that the heat of condensation released during convection over the IPWP sets the temperature above ~4 km in the tropics (Broecker 1997). The relative abundance of the oxygen isotopes ^{18}O and ^{16}O (expressed as $\delta^{18}O$) is the most common parameter measured in tropical ice cores. If the initial $\delta^{18}O$ of water vapor condensing to yield snow is constant, then the resulting $\delta^{18}O$ of the snow will be a function of both condensation temperature and precipitation amount (Pierrehumbert 1999; Lawrence and Gedzelman 2003). In tropical ice cores, seasonal oscillations in $\delta^{18}O$ show an apparent inverse relationship with temperature, in contrast to $\delta^{18}O$ values in polar ice (Dansgaard 1964). This is because seasonal variations in the $\delta^{18}O$ of high-altitude tropical precipitation reflect the temperature of the mean condensation level, which is significantly higher (and colder) during the summer wet season in the tropics (Thompson et al. 2000). On the other hand, seasonal changes in the precipitation "amount effect" on $\delta^{18}O$ may overwhelm the effect of seasonal changes in temperature on the $\delta^{18}O$ of tropical ice (Bradley et al. 2003; Hardy et al. 2003). However, because

70%–80% of tropical precipitation falls during the summer wet season, tropical ice core $\delta^{18}O$ is dominated by the wet season temperature. Despite these high-frequency seasonal variations, $\delta^{18}O$ in tropical ice is positively correlated with global temperature over centennial-millennial time scales, and accurately records twentieth-century warming (Thompson et al. 2003). Therefore, although it is somewhat counterintuitive, evidently large seasonal variations in the $\delta^{18}O$ of tropical ice produced by the seasonal contrast in precipitation amount are superimposed on long-term ice core $\delta^{18}O$ trends where changes in air temperature dominate the mean climate signal.

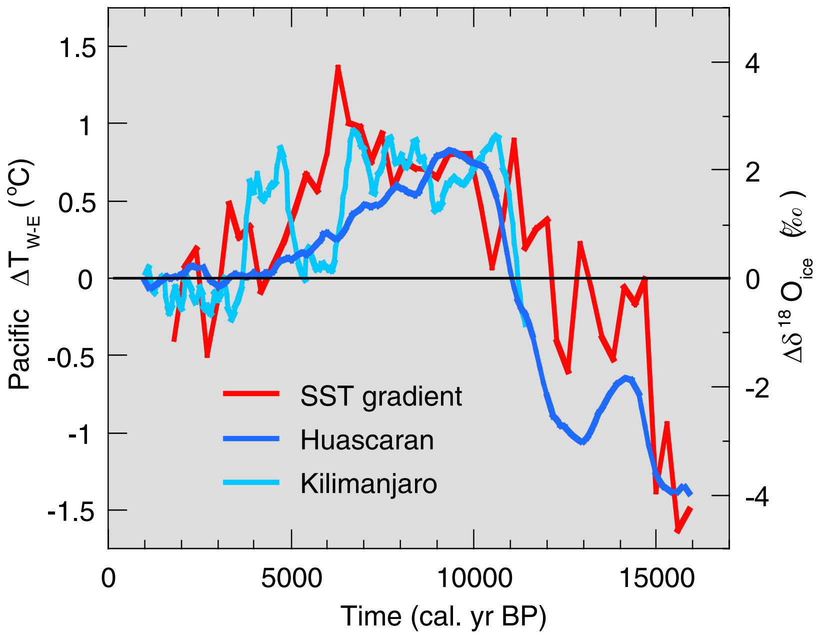

Figure 10-4. Comparison of changes in the east-west SST gradient (ΔT_{W-E}) across the tropical Pacific and $\delta^{18}O$ in high-elevation tropical ice cores from Huascarán, Peru (09°07' S, 77°37' W; 6,048 m above sea level (masl); Thompson et al. 1995) and Mt. Kilimanjaro, Tanzania (03°04.6' S, 37°21.2' E; 5,893 masl; Thompson et al. 2002). Ice core data have been smoothed with a 500-year running mean and normalized to the mean late Holocene $\delta^{18}O$ values.

Figure 10-4 shows late-glacial and Holocene $\delta^{18}O$ values in the high-altitude ice core from Huascarán, located at 9°S in the Cordillera

Blanca of Peru (Thompson et al. 1995). The striking feature in the Huascarán ice core record is the high $\delta^{18}O$ values between 11,000 and 4,000 BP. If temperature was the dominant forcing, then the $\delta^{18}O$ in the Huascarán ice core suggests that the early Holocene was ~1.5°C–2°C warmer, relative to the late Holocene (Thompson et al. 1995; Bradley et al. 2003). The recent discovery of tropical plants exposed from beneath the retreating Peruvian Quelccaya Ice Cap, with radiocarbon dates of 5.18 ± 0.45 thousand years BP, indicates that conditions were indeed warmer in the high near-equatorial Andes.

A high-altitude equatorial ice core $\delta^{18}O$ record for Mt Kilimanjaro, Tanzania (Thompson et al. 2002), provides a means for determining if, as suggested, transport of latent heat from the IPWP to the equatorial middle troposphere was a general feature of the La Niña–like state in Pacific SSTs during the early Holocene. The climate of equatorial east Africa was relatively wet during the early Holocene, so the precipitation amount effect on the $\delta^{18}O$ of Kilimanjaro ice should be opposed to any early Holocene warming signal. The results show that the early Holocene warming in the Kilimanjaro $\delta^{18}O$ record is in good agreement with that observed in the Huascarán ice core record (Fig. 10-4). Taken together, the records suggest that long-term changes in precipitation amount had a minor influence on the $\delta^{18}O$ of the ice core records and that, instead, widespread warming of the middle troposphere occurred in response to warming of the IPWP during the early Holocene.

We note that ice core $\delta^{18}O$ data for Sajama, Bolivia, at 18°S indicate that the climate was cooler/wetter when Huascarán (9°S) was warmer. The pattern is suggestive of a northward shift in the mean annual position of the Intertropical Convergence Zone (ITCZ). Geochemical records from deep-sea sediment cores from the Cariaco Basin, in the tropical North Atlantic, indicate intensified ITCZ rainfall during the early Holocene, in response to higher summer insolation in the Northern Hemisphere (Haug et al. 2001). In contrast, the level of Lake Titicaca in the Andean altiplano was at its lowest in the last 25,000 years during the early to middle Holocene (Baker et al. 2001). Therefore, the opposing signals in the Huascarán and Sajama $\delta^{18}O$ records may reflect changes in the position of the ITCZ and the location of ascending and descending air masses within the Hadley circulation (Thompson et al. 2000). If the mean position of the ITCZ was shifted towards the north, Huascarán would tend to be warm and dry beneath the descending limb of the Hadley cell. Sajama, on the other hand, could be cooler and wetter during the early Holocene under the influence of enhanced easterly airflow and precipitation, as observed during modern La Niña events (Vuille 1999; Bradley et al. 2003; Hardy et al. 2003). The mid- to late Holocene shift to modern $\delta^{18}O$ values may reflect a southward migration of the Hadley circulation that is coeval with the intensification of Southern Hemisphere summer insolation (Haug et al. 2001; Seltzer et al. 2002).

4. INFLUENCE OF THE TROPICS ON POST-GLACIAL WARMING AT HIGH LATITUDES

Widespread warming of the tropics should generate a globally synchronous climate response to Milankovitch forcing, without a net increase in global solar radiation. A tropical influence on the climate of the higher latitudes would explain why ice sheets and glaciers in the Southern Hemisphere decayed almost synchronously with those in the Northern Hemisphere, despite the decrease in Southern Hemisphere summer insolation during deglaciation (Karner and Muller 2000). Our knowledge of post-glacial air temperature changes over Antarctica has grown recently through the development of deuterium isotopic profiles (δD) in five ice cores from the East Antarctic plateau (see summary by Jouzel et al. 2001). The δD record in ice from Vostok, Antarctica, is typical of the five cores in showing a strong late glacial (~11,000 years) warming step culminating with an early to middle Holocene optimum (Petit et al. 1999). While the details are different, the timing of the early Holocene warming and the cooling trend to ~4,000 years ago is approximately synchronous with the warming observed in tropical ice cores, and the enhanced La Niña–like state in the Pacific (Fig. 10-5).

The correlation between the development of a La Niña–like state in Pacific SSTs and atmospheric warming in the Southern Hemisphere is interesting because it is opposite to the observation that La Niña years produce cooler surface temperatures in North America (Cane 1998). Moreover, model studies indicate that a La Niña–like state in Pacific SSTs should promote the growth of Northern Hemisphere ice sheets and planetary cooling (Cane and Clement 1999). The early Holocene warming in the tropics and Southern Hemisphere leads and exceeds the warming observed in ice $\delta^{18}O$ records from the GRIP and GISP2 sites in central Greenland (Fig. 10-5; Grootes et al. 1993). On the other hand, temperature profiles measured down through the GRIP borehole indicate that mean annual temperatures in the early Holocene were 2.5°C warmer, relative to the last ~500 years (Dahl-Jensen et al. 1998). While the nature of the mean air temperature trend over Greenland is still controversial, several lines of evidence show that summer air temperatures in the Arctic were indeed warmer during the early Holocene than they are today. For example, melt layers and $\delta^{18}O$ records from low-elevation Canadian Arctic ice caps (Agassiz [Fisher et al. 1995]; Devon [Koerner 1977]) show the warmest summer temperatures during the early Holocene, followed by long-term summer cooling (see reviews by Bradley et al. 2003; Fisher and Koerner 2003).

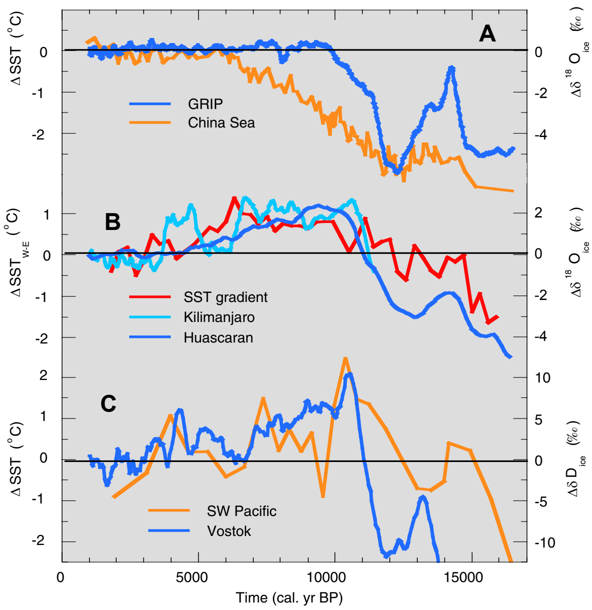

Figure 10-5. Interhemispheric comparison of the post-glacial timing of changes in SST and air temperature in the tropics, Greenland, and Antarctica. (A) Lag of change in SSTs reconstructed from alkenone unsaturation ratios in deep-sea core 17940 from the South China Sea (20°07'N, 117°23'E; Pelejero et al. 1999) relative to the change of $\delta^{18}O$ in the GRIP Greenland ice core (Grootes et al. 1993). (B) Synchronous changes in the east-west SST gradient across the tropical Pacific and $\delta^{18}O$ in ice cores from Huascarán, Peru (Thompson et al. 1995) and Mt. Kilimanjaro, Tanzania (Thompson et al. 2002). (C) Comparison of Southern Hemisphere mid-latitude SSTs reconstructed from Mg/Ca in the planktonic foraminifer *Globigerina bulloides* in deep-sea core MD97-2120 from the Chatham Rise, east of New Zealand (45°32.06'S, 174°55.85'E; Pahnke et al. 2003) and the change of δD in ice from Vostok, Antarctica (Petit et al. 1999). All data are normalized relative to late Holocene values. Ice core data have been smoothed with a 500-year running mean for comparison with relatively coarse-resolution marine records.

A picture is emerging for the tropics and Southern Hemisphere of early post-glacial warming culminating in an early Holocene climatic optimum. However, even when conventional feedbacks are considered, such as changes in ocean thermohaline circulation, increases in atmospheric CO_2, and decreasing atmospheric dust, they appear to be incapable of inducing a 3°C–5°C post-glacial rise in tropical temperatures by the early Holocene. In the next section, we examine potential mechanisms by which increasing Northern Hemisphere insolation could serve to invigorate the Hadley circulation, increase the SST contrast between the Pacific cold tongue and IPWP, and thus bring about the unanticipated warming of the tropics and Southern Hemisphere during the early Holocene.

5. MILANKOVITCH FORCING OF THE TROPICAL OCEAN-ATMOSPHERE AND GLOBAL WARMING

5.1. The Hadley Circulation and Southern Hemisphere Warming

Changes in solar radiation at the top of the atmosphere associated with Milankovitch forcing are exceedingly small when averaged annually. Thus the warming of the tropics and Southern Hemisphere during the late glacial and early Holocene requires mechanisms that can amplify seasonal changes in insolation forcing at a specific latitude. Modeling studies show that changes in latitudinal temperature gradients play a key role in the equator-to-pole heat flux (Rind 1998 2000) and change the mean temperature of the earth (Lindzen and Pan 1994). Warming of IPWP SSTs (and the tropical troposphere) would, in general, serve to increase the equator-to-pole heat flux and warm high latitudes. This process, together with the increase in Northern Hemisphere summer insolation and associated ice albedo feedback, would have warmed the Northern Hemisphere high latitudes during deglaciation. However, the ice core records indicate that post-glacial warming in the Southern Hemisphere was closely synchronized with the warming in the tropics. Thus a more direct link between the tropics and the Southern Hemisphere must be acting to transport additional heat to Antarctica.

Results of a simplified general circulation model (GCM) and heat transport calculations show that even a slight shift (2^o latitude) of the mean tropical heating off the equator leads to a more intense cross-equatorial "winter" Hadley circulation accompanied by warming of the winter high latitudes (Lindzen and Hou 1988; Hou 1993). As the heating center (ITCZ) moves off the equator toward the summer hemisphere, the Hadley circulation extending into the winter hemisphere becomes more intense while the summer cell becomes much weaker. Thus, under asymmetrical heating in the tropics, poleward heat transport is significantly a winter hemisphere phenomenon. Calculations also show that the annually averaged asymmetrical Hadley circulation is stronger than the equinoctial circulation (Lindzen and Hou 1988). The results indicate that the annually averaged climate of middle to high latitudes may be dependent on the summer-winter asymmetry in insolation forcing brought about by precession of the equinoxes (Lindzen and Pan 1994), even though the insolation asymmetry does not contribute to the annually averaged heating.

This mechanism of intensification of the Hadley circulation provides interesting possibilities for heating the Southern Hemisphere synchronously with the northward movement of the ITCZ into the Northern Hemisphere under the influence of enhanced summer insolation during the early Holocene. It is now well established that the northward asymmetry in summer insolation during the early Holocene acted to shift the annual mean position of the ITCZ north of the equator (e.g. Haug et al. 2001; Morrill et al 2003). Northern Hemisphere summer heating of the Asian landmass, in particular, caused significant strengthening of the Asian monsoon and a profound northward distortion of the mean position of the center of tropical heating (see review by Morrill et al. 2003).

Thus the heat budget of the high latitudes of the Southern Hemisphere in winter during the late glacial and early Holocene may have been primarily determined by Hadley circulation dynamics while, for the Northern Hemisphere, local radiative budgets were probably more important (Webster 1982). Given that ocean surface temperatures in summer are strongly influenced by winter heat fluxes because of the large heat capacity of the oceans, year-round warming of the Southern Hemisphere could have been produced by poleward heat transport during the winter (Lindzen and Pan 1994).

5.2. Coupling of the Tropical Ocean-Atmosphere and Greenhouse Gas Concentrations

It is generally accepted that the oceans played a significant role in promoting changes in atmospheric CO_2 concentrations during glacial-interglacial cycles (Broecker 1982). The observed La Niña–like state in Pacific SSTs during the late glacial and early Holocene is consistent with the rapid rise of CO_2 trapped in polar ice cores (Indermühle et al. 1999; Petit et al. 1999). During La Niña events, the area of high $p\mathrm{CO_2}$ equatorial cold tongue water expands towards the west (Feely et al. 1995). Such an SST configuration could play a role in the late glacial and early Holocene warming because the cold tongue area of the equatorial Pacific is the site of the greatest evasion of CO_2 (0.8–1.0 Pg C/yr) from the modern oceans (Takahashi et al. 2002).

Recently, Palmer and Pearson (2003) produced a boron isotope record for planktonic foraminifera from the western equatorial Pacific to reconstruct the pH of surface seawater and, by inference, pCO_2 over the last 25,000 years. The results indicate that the equatorial Pacific was a significant source of CO_2 to the atmosphere between 15,600 and 13,800 years ago. The timing of the peak in the pCO_2 is coincident with the steepest rise in atmospheric CO_2 levels during the last deglaciation (Indermühle et al. 1999; Petit et al. 1999), and the anomaly is best explained if there were more frequent and/or more intense La Niña events (Palmer and Pearson 2003). Therefore, an increase in atmospheric CO_2 potentially brought about by the intensification of the Hadley-Walker circulation and La Niña–like SST configuration could certainly have contributed to the late glacial warming and early Holocene temperature maximum. However, given that the shift in atmospheric pCO_2 from the LGM to the Holocene (~90 parts per million by volume [ppmv]) is associated with far more warming than has been observed under similar greenhouse-gas forcing during the twentieth century, additional mechanisms must be contributing to the warming.

The widespread and synchronous late glacial to early Holocene warming signal suggests that water vapor, the most important greenhouse gas, must somehow be involved. Surface-ocean evaporation becomes strongly nonlinear above SSTs of 28°C (Webster 1994), and drives tropical convection. The paleoclimate records suggest that, on long time scales at least, the flux of water vapor and heat brought about by enhanced IPWP evaporation and convection during the La Niña state overwhelmed any atmospheric cooling due to expansion of the East Pacific cold tongue. Evaporation near convective cloud tops humidifies the atmosphere at high altitudes, reduces the Earth's energy emission to space, and thus warms the atmosphere (Pierrehumbert 2000). Although still a matter of considerable debate, it has been suggested that a post-glacial rise in the absolute water vapor content of the atmosphere could produce a 2°C global warming. Taken together, the results indicate that the Hadley-Walker circulation system and the IPWP–cold tongue configuration could have conspired to increase the atmospheric concentrations of CO_2 and water vapor, resulting in widespread early Holocene warming.

6. THE 11,000 TO 4,000 BP TURN-ON OF SOUTHERN HEMISPHERE WARMING

What caused tropical SSTs and Southern Hemisphere air temperatures to equal or exceed late Holocene values from ~11,000 to 4,000 years ago? We envisage three primary processes that led to the abrupt "turn-on" of warming at ~11,000 years ago and "turn-off" at ~4,000 years ago:

(1) The timing of maximum warming observed in the IPWP SSTs and Southern Hemisphere ice core records coincides with the ~11,000-year maximum in Northern Hemisphere summer (July) insolation at 65°N. The off-equatorial heating and resulting southward-directed heat flux of the Hadley circulation at this time would have promoted the temperature maximum in the Southern Hemisphere high latitudes. A synchronous increase in the east-west SST gradient across the Pacific may have superimposed a greenhouse-gas feedback contributing to more widespread warming Thus, the initiation of the late glacial to early Holocene stage of the warming would have been driven primarily by changes in ocean-atmosphere dynamics associated with the maximum in Northern Hemisphere summer insolation.

(2) It is possible that as the Northern Hemisphere summer insolation anomaly weakened, continued invigoration of the Pacific cold tongue–warm pool SST contrast may have served to extend global warming into the mid-Holocene, as indicated by the paleo records. A semipermanent La Niña–like state during the mid-Holocene has been suggested by recent model studies of the direct effect of orbitally induced changes in the seasonal distribution of insolation on the tropical ocean-atmosphere system. Clement et al. (2000) attributed a suppression of the early to mid-Holocene ENSO to the peak in insolation on the equator during the boreal summer/fall brought about by precession of the earth's equinoxes. According to the numerical model, the additional heating of equatorial Pacific surface waters in the boreal summer/fall during the early to mid-Holocene produces an easterly wind anomaly that suppresses the development of El Niño events. Ocean-atmosphere feedbacks drive the ENSO system towards a La Niña state by increasing SST and pressure gradients across the Pacific, in good agreement with the paleoclimate records.

A similar effect has been observed in a global coupled ocean-atmosphere model, whereby the intensified Asian monsoon during the early Holocene further enhances Pacific trade winds, thus cooling the eastern equatorial Pacific and reducing ENSO interannual variability (Liu et al. 2000). Northward transport of warm SST anomalies from the subtropical South Pacific into the equatorial Pacific thermocline via the meridional circulation may also serve to subdue El Niño SST anomalies (Liu et al. 2000), and create a La Niña–like state in mean Pacific SSTs.

(3) The demise of tropical warming at ~4,000 BP appears to correlate with the onset of modern ENSO variability between ~4,000 and 7,000 years ago (Rodbell et al. 1999; Moy et al. 2002) and may signal the onset of coordinated heat removal from the tropical Pacific. Today, the periodic relaxation of the tropical Pacific ocean-atmosphere system during El Niño events provides an efficient mechanism for releasing heat accumulated in the tropical western Pacific (Sun and Trenberth 1998). Evidence for the demise of the suppressed ENSO in the mid-Holocene is most clear in the tropical eastern Pacific and northern South America. Spectral analysis of the 15,000-year high-resolution record of storm-derived clastic sedimentation in Laguna Pallcacocha, Ecuador (Rodbell et al. 1999; Moy et al. 2002) shows that the transition to modern ENSO periodicities (2–8 yr) began ~7,000–5,000 years ago (Fig. 10-3). A similar conclusion was reached by Sandweiss et al. (1996), based on their analysis of fossil mollusk assemblages and geoarcheological evidence from coastal Peru.

More indirect evidence of Holocene ENSO variability is provided by titanium concentrations in sediment from Ocean Drilling Project (ODP) site 1002 in the Cariaco Basin, off northern Venezuela (Haug et al. 2001). Titanium concentrations in Cariaco Basin sediments reflect variations in runoff associated with shifts in the position of the ITCZ. Enhanced runoff variability beginning ~3,800 years ago indicates a mean southward shift in the position of the ITCZ thought to be linked to the strengthening of El Niño events. In addition, a recent synthesis of paleoclimate records for the Asian monsoon reveals an abrupt reduction in monsoon intensity ~4,500–5,000 years ago across the entire Asian monsoon domain (Morrill et al. 2003). According to the paleo-ENSO models of Liu et al. (2000), the associated reduction in trade wind velocity across the Pacific would have served to enhance ENSO variability and reduce the east-west SST gradient across the equatorial Pacific.

7.` WILL OCEAN-ATMOSPHERE DYNAMICS CONTRIBUTE TO FUTURE WARMING?

Transient greenhouse warming simulations suggest that the distribution of global warming will not be homogeneous in the twenty-first century, and that large-scale changes in surface temperature gradients and atmospheric circulation may result (Cai and Whetton 2000). Recently, Anderson et al. (2002) argued that an increase in Asian monsoon intensity during the twentieth century is related to Northern Hemisphere air temperature changes during the past century. The effect of accelerated heating of the Asian landmass, relative to the tropical ocean, would be to pull the mean annual position of the ITCZ north of the equator. Such a northward shift of the center of tropical convection should invigorate the Hadley circulation and warm the Southern Hemisphere high latitudes.

Several recent studies have noted changes in the tropical energy budget related to a strengthening of the Hadley-Walker circulations during the 1990s (e.g., Chen et al. 2002; Hoerling and Kumar 2003). The alteration of the tropical general circulation was associated with intensified ascending motion and moistening of the equatorial convective regions and stronger sinking motion and drying of the equatorial and subtropical subsidence regions. Such a scenario is similar to that associated with the La Niña–like state in Pacific SSTs during the early Holocene. Indeed, a persistent La Niña from 1998 through 2002, together with above average SSTs in the western Pacific, have been linked with warming and drying of the mid-latitudes of both hemispheres (Barlow et al. 2002; Hoerling and Kumar 2003.).

While the ocean-atmosphere feedbacks identified for the early Holocene warming provide only partial analogues for a climate that may be influenced by greenhouse-gas forcing, both the paleo data and recent observations indicate that a strengthening of the tropical general circulation may well amplify any warming produced by enhanced levels of atmospheric CO_2.

8. ACKNOWLEDGMENTS

We thank Ray Bradley and Henry Diaz for organizing the "Hadley Circulation: Present, Past and Future" meeting in November 2002 at the University of Hawaii, which provided fuel for thought when we wrote this chapter. Peter Isdale and David Hopley kindly provided access to their suites of modern and fossil coral cores for the paleoclimate reconstructions for the Great Barrier Reef. Bambang Suwargadi, Dudi Prayudi, and Anto Sanyoto of the Indonesian Institute of Sciences are warmly thanked for dedicated assistance during coral drilling expeditions in Indonesia. Particular thanks go to Joe Cali, Graham Mortimer, and Heather Scott-Gagan for skillful mass spectrometry in the Research School of Earth Sciences laboratories. The collaborative contributions of Linda Ayliffe, Wahyoe Hantoro, and Malcolm McCulloch toward the production of the coral records reviewed in this chapter are greatly appreciated. Support for MKG's research in the Great Barrier Reef and Indonesia was provided by The Australian National University.

9. REFERENCES

Anderson, D.M., J.T. Overpeck, and A.K. Gupta. 2002. Increase in the Asian southwest monsoon during the past four centuries. *Science* 297: 596–599.

Baker, P.A., G.O. Seltzer, S.C. Fritz, R.B. Dunbar, M.J. Grove, P.M. Tapia, S.L. Cross, H.D. Rowe, and J.P Broda. 2001. The history of South American tropical precipitation for the past 25,000 years. *Science* 291: 640–643.

Barlow, M., H. Cullen, and B. Lyon. 2002. Drought in central and southwest Asia: La Niña, the warm pool, and Indian Ocean precipitation. *Journal of Climate* 15: 697–700.

Beck, J.W., R.L. Edwards, E. Ito, F.W. Taylor, J. Récy, F. Rougerie, P. Joannot, and C. Henin. 1992. Sea-surface temperature from coral skeletal strontium/calcium ratios. *Science* 257: 644–647.

Beck, J.W., J. Récy, F. Taylor, R.L. Edwards, and G. Cabioch. 1997. Abrupt changes in early Holocene tropical sea surface temperature derived from coral records. *Nature* 38: 705–707.

Bjerknes, J., 1966: A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature. *Tellus* 18: 820–829.

Bjerknes, J. 1969. Atmospheric teleconnections from the equatorial Pacific. *Monthly Weather Review* 97: 163–172.

Bradley, R.S., K.R. Briffa, J.E. Cole, M.K. Hughes, and T.J. Osborn. 2003. The climate of the last millennium. In, Alverson, K., R.S. Bradley, and T.F. Pedersen (eds.). *Paleoclimate, Global Change and the Future.* Berlin: Springer-Verlag, pp. 105–141.

Bradley, R.S., M. Vuille, D. Hardy, and L.G. Thompson. 2003. Low latitude ice cores record Pacific sea surface temperatures. *Geophysical Research Letters* 30(4): 1174, doi:10.1029/2002GL016546.

Broecker, W.S. 1982. Glacial to interglacial changes in ocean chemistry. *Progress in Oceanography* 11: 151–197.

Broecker, W.S. 1997. Mountain glaciers: Recorders of atmospheric water vapor content? *Global Biogeochemical Cycles* 11: 589–597.

Cai, W., and P.H. Whetton. 2000. Evidence for a time-varying pattern of greenhouse warming in the Pacific Ocean. *Geophysical Research Letters* 27: 2577–2580.

Cane, M.R. 1998. A role for the tropical Pacific. *Science* 282: 59–61.

Cane, M.R., and A.C. Clement. 1999. A role for the tropical Pacific coupled ocean-atmosphere system on Milankovitch and millennial timescales: Part II: Global impacts. *Mechanisms of Global Climate Change at Millennial Time Scales. Geophysical Monograph* 112: 373–383.

Chen, J., B.E. Carlson, and A.D. Del Genio. 2002. Evidence for strengthening of the tropical general circulation. *Science* 295: 838–841.

Clement, A., M. Cane, and R. Seager. 2001. An orbitally driven tropical source for abrupt climate change. *Journal of Climate* 14: 2369–2375.

Clement, A.C., R. Seager, and M.A. Cane. 2000. Suppression of El Niño during the mid-Holocene by changes in the Earth's orbit. *Paleoceanography* 15: 731–737.

Corrège, T., T. Delcroix, J. Recy, W. Beck, G. Cabioch, and F. Le Cornec. 2000. Evidence for stronger El Niño–Southern Oscillation (ENSO) events in a mid-Holocene massive coral. *Paleoceanography* 14: 465–470.

Dahl-Jensen, D., K. Mosegaard, N. Gundestrup, G.D. Clow, S.J. Johnsen, A.W. Hansen, and N. Balling. 1998. Past temperatures directly from the Greenland ice sheet. *Science* 282: 268–271.

Dansgaard, W. 1964. Stable isotopes in precipitation. *Tellus* 16: 436–468.

de Villiers, S., G.T. Shen, and B.K. Nelson. 1994. The Sr/Ca-temperature relationship in coralline aragonite: Influence of variability in $(Sr/Ca)_{seawater}$ and skeletal growth parameters. *Geochimica et Cosmochimica Acta* 58: 197–208.

Feely, R.A., R. Wanninkhof, C.E. Cosca, P.P. Murphy, M.F. Lamb, and M.D. Steckley. 1995. CO_2 distribution in the equatorial Pacific during the 1991–92 ENSO event. *Deep-Sea Research* II 42: 365–386.

Fisher, D.A., and R.M. Koerner. 2003. Holocene ice-core climate history—A multivariable approach. In, Mackay, A.W., R.W. Battarbee, H.J.B. Birks, and F. Oldfield. *Global Change in the Holocene: Approaches to Reconstructing Fine-Resolution Climate Change.* London: Arnold, pp. 281–293.

Fisher, D.A., R.M. Koerner, and N. Reeh. 1995. Holocene climatic records from Agassiz Ice Cap, Ellesmere Island, NWT, Canada. *The Holocene* 5: 19–24.

Gagan, M.K., L.K. Ayliffe, J.W. Beck, J.E. Cole, E.R.M. Druffel, R.B. Dunbar, and D.P. Schrag. 2000. New views of tropical paleoclimates from corals. *Quaternary Science Reviews* 19: 45–64.

Gagan, M.K., L.K. Ayliffe, D. Hopley, J.A. Cali, G.E. Mortimer, J. Chappell, M.T. McCulloch, and M.J. Head. 1998. Temperature and surface-ocean water balance of the mid-Holocene tropical western Pacific. *Science* 279: 1014–1018.

Gagan, M.K., E.J. Hendy, S.G. Haberle, and W.S. Hantoro. 2004. Post-glacial evolution of the Indo-Pacific Warm Pool and El Niño–Southern Oscillation. *Quaternary International* 118–119: 127–143.

Grootes, P.M., M. Stuiver, J.W.C. White, S. Johnsen, and J. Jouzel. 1993. Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. *Nature* 366: 552–554.

Hardy, D.R., M. Vuille, and R.S. Bradley. 2003. Variability of snow accumulation and isotopic composition on Nevado Sajama, Bolivia. *Journal of Geophysical Research* 108: D22, 4693, doi:10.1029/2003JD003623, 2003.

Haug, G.H., K.A. Hughen, D.M. Sigman, L.C. Peterson, and U. Rohl. 2001. Southward migration of the intertropical convergence zone through the Holocene. *Science* 293: 1304–1308.

Hendy, E.J., M.K. Gagan, C.A. Alibert, M.T. McCulloch, J.M. Lough, and P.J. Isdale. 2002. Abrupt decrease in tropical Pacific sea surface salinity at end of Little Ice Age. *Science* 295: 1511–1514.

Hoerling, M., and A. Kumar. 2003. The perfect ocean for drought. *Science* 299: 691–694.

Hou, A.Y. 1993. The influence of tropical heating displacements on the extratropical climate. *Journal of Atmospheric Science* 50: 3553–3570.

Hou, A.Y. 1998. Hadley circulation as a modulator of the extratropical climate. *Journal of Atmospheric Science* 55: 2437–2457.

Indermühle, A., T.F. Stocker, F. Joos, H. Fischer, H.J. Smith, M. Wahlen, B. Deck, D. Mastroianni, J. Tschumi, T. Blunier, R. Meyer, and B. Stauffer. 1999. Holocene carbon-cycle dynamics based on CO_2 trapped in ice at Taylor Dome, Antarctica. *Nature* 398: 121–126.

Jouzel, J., V. Masson, O. Cattani, S. Falourd, M. Stievenard, B. Stenni, A. Longinelli, S.J. Johnsen, J.P. Steffenssen, J.R. Petit, J. Schwander, R. Souchez, and N.I. Barkov. 2001. A new 27 ky high resolution East Antarctic climate record. *Geophysical Research Letters* 28: 3199–3202.

Karner, D.B., and R.A. Muller. 2000. A causality problem for Milankovitch. *Science* 288: 2143–2144.

Keigwin, L.D. 1978. Pliocene closing of the Isthmus of Panama based on biostratigraphic evidence from nearby Pacific Ocean and Caribbean Sea cores. *Geology* 6: 630–634.

Kienast, M., S. Steinke, K. Stattegger, and S.E. Calvert. 2001. Synchronous tropical south China Sea SST change and Greenland warming during deglaciation. *Science* 291: 2132–2134.

Koerner, R.M. 1977. Devon Island ice cap: Core stratigraphy and paleoclimate. *Science* 196: 15–18.

Koutavas, A., J. Lynch-Stieglitz, T.M. Marchitto, Jr., and J.P. Sachs. 2002. El Niño–like pattern in ice age tropical Pacific sea surface temperature. *Science* 297: 226–230.

Lawrence, J.R., and S.D. Gedzelman. 2003. Tropical ice core isotopes: Do they reflect changes in storm activity? *Geophysical Research Letters* 30(2): 1072, doi:10.1029/2002GL015906.

Lea, D.W., D.K. Pak, and H.J. Spero. 2000. Climate impact of late Quaternary equatorial Pacific sea surface temperature variations. *Science* 289: 1719–1724.

Lindzen, R.S., and A.Y. Hou. 1988. Hadley circulation for zonally averaged heating centered off the equator. *Journal of Atmospheric Science* 45: 2417–2427.

Lindzen, R.S., and W. Pan. 1994. A note on orbital control of equator-to-pole heat fluxes. *Climate Dynamics* 10: 49–57.

Liu, Z. 1998. The role of ocean in the response of tropical climatology to global warming: The west-east contrast. *Journal of Climate* 11: 864–875.

Liu, Z., and B. Huang. 1997. A coupled theory of tropical climatology: Warm Pool, cold tongue, and Walker circulation. *Journal of Climate* 10: 1662–1679.

Liu, Z., J. Kutzbach, and L. Wu. 2000. Modeling climate shift of El Niño variability in the Holocene. *Geophysical Research Letters* 27: 2265–2268.

McCulloch, M.T., G. Mortimer, T. Esat, L. Xianhua, B. Pillans, and J. Chappell. 1996. High resolution windows into early Holocene climate: Sr/Ca coral records from the Huon Peninsula. *Earth and Planetary Science Letters* 138: 169–178.

McGregor, H.V., and M.K. Gagan. 2003. Diagenesis and geochemistry of *Porites* corals from Papua New Guinea: Implications for palaeoclimate reconstruction. *Geochimica et Cosmochimica Acta* 67: 2147–2156.

Meyers, G. 1996. Variation of Indonesian throughflow and the El Niño–Southern Oscillation. *Journal of Geophysical Research* 101: 12255–12263.

Morrill, C., J.T. Overpeck, and J.E. Cole. 2003. A synthesis of abrupt changes in the Asian summer monsoon since the last deglaciation. *The Holocene* 13: 465–476.

Moy, C.M., G.O. Seltzer, D.T. Rodbell, and D.M. Anderson. 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature* 420: 162–165.

Müller, A., M.K. Gagan, and M.T. McCulloch. 2001. Early marine diagenesis in corals and geochemical consequences for paleoceanographic reconstructions. *Geophysical Research Letters* 28: 4471–4474.

Pahnke, K., R. Zahn, H. Elderfield, and M. Schulz. 2003. 340,000-year centennial-scale marine record of Southern Hemisphere climatic oscillation. *Science* 301: 948–952.

Palmer, M.R., and P.N. Pearson. 2003. A 23,000-year record of surface water pH and pCO_2 in the western equatorial Pacific Ocean. *Science* 300: 480–482.

Pelejero, C., J.O. Grimalt, S. Heilig, M. Kienast, and L. Wang. 1999. High-resolution U^k_{37} temperature reconstructions in the South China Sea over the past 220 kyr. *Paleoceanography* 14: 224–231.

Petit, J.R., J. Jouzel, D. Raynaud, N.I. Barkov, J.-M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Delmotte, V.M. Kotlyakov, M. Legrand, V.Y. Lipenkov, C. Lorius, L. Pepin, C. Ritz, E. Saltzman, and M. Stievenard. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* 326: 273–277.

Philander, S.G., and A.V. Federov. 2003. Role of the tropics in changing the response to Milankovitch forcing some three million years ago. *Paleoceanography* 18(2), 1045, doi:10.1029/2002PA000837.

Pierrehumbert, R.T. 1999. Huascarán $\delta^{18}O$ as an indicator of tropical climate during the Last Glacial Maximum. *Geophysical Research Letters* 26: 1345–1348.

Pierrehumbert, R.T. 2000. Climate change and the tropical Pacific: The sleeping dragon wakes. *Proceedings of the National Academy of Science* 97: 1355–1358.

Rind, D. 1998. Latitudinal temperature gradients and climate change. *Journal of Geophysical Research* 103: 5943–5971.

Rind, D. 2000. Relating paleoclimate data and past temperature gradients: Some suggestive rules. *Quaternary Science Reviews* 19: 381–390.

Rodbell, D.T., G.O. Seltzer, D.M. Anderson, M.B. Abbott, D.B. Enfield, and J.H. Newman. 1999. An ~15,000-year record of El Niño–driven alluviation in southwestern Ecuador. *Science* 283: 516–520.

Romine, K. 1982. Late Quaternary history of atmospheric and oceanic circulation in the eastern equatorial Pacific. *Marine Micropaleontology* 7: 163–187.

Rosenthal, Y., D.W. Oppo, and B.K. Linsley. 2003. The amplitude and phasing of climate change during the last deglaciation in the Sulu Sea, western equatorial Pacific. *Geophysical Research Letters* 30(8): 1428, doi:10.1029/2002GL016612.

Sandweiss, D.H., J.B. Richardson, III, E.J. Reitz, H.B. Rollins, and K.A. Maasch. 1996. Geoarchaeological evidence from Peru for a 5000 B.P. onset of El Niño. *Science* 273: 1531–1533.

Seltzer, G.O., D.T. Rodbell, P.A. Baker, S.C. Fritz, P.M. Tapia, H.D. Rowe, and R.B. Dunbar. 2002. Early warming of tropical South America at the last glacial-interglacial transition. *Science* 296: 1685–1686.

Stott, L., C. Poulsen, S. Lund, and R. Thunell. 2002. Super ENSO and global climate oscillations at millennial time scales. *Science* 297: 222–226.

Sun, D.-Z., and K.E. Trenberth. 1998. Coordinated heat removal from the equatorial Pacific during the 1986–87 El Niño. *Geophysical Research Letters* 25: 2659–2662.

Takahashi, T., S.C. Sutherland, C. Sweeney, A. Poisson, N. Metzl, B. Tilbrook, N. Bates, R. Wanninkhof, R.A. Feely, C. Sabine, J. Olafsson, and Y. Nojiri. 2002. Global sea-air CO_2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects. *Deep-Sea Research* II 49: 1601–1622.

Thompson, L.G., M.E. Davis, E. Mosley-Thompson, T.A. Sowers, K.A. Henderson, V.S. Zagorodnov, P.-N. Lin, V.N. Mikhalenko, R.K. Campen, J.F. Bolzan, J.A. Cole-Dai, and B. Francou. 1998. A 25,000-year tropical climate history from Bolivian ice cores. *Science* 282: 1858–1864.

Thompson, L.G., E. Mosley-Thompson, and K.A. Henderson. 2000. Ice-core palaeoclimate records in tropical South America since the Last Glacial Maximum. *Journal of Quaternary Science* 15(4): 377–394.

Thompson, L.G., E. Mosley-Thompson, M.E. Davis, K.A. Henderson, H.H. Brecher, V.S. Zagorodnov, T.A. Mashiotta, P.-N. Lin, V.N. Mikhalenko, D.R. Hardy, and J. Beer. 2002. Kilimanjaro ice core records: Evidence of Holocene climate change in tropical Africa. *Science* 298: 589–593.

Thompson, L.G., E. Mosley-Thompson, M.E. Davis, P.-N. Lin, K.A. Henderson, J. Cole-Dai, J.F. Bolzan, and K.-b. Liu. 1995. Late glacial stage and Holocene tropical ice core records from Huascarán, Peru. *Science* 269: 46–50.

Thompson, L.G., E. Mosley-Thompson, M.E. Davis, P.-N. Lin, K. Henderson, and T.A. Mashiotta. 2003. Tropical glaciers and ice core evidence of climate change on annual to millennial time scales. *Climatic Change* 59: 137–155.

Tudhope, A.W., C.P. Chilcott, M.T. McCulloch, E. Cook, J. Chappell, R.M. Ellam, D.W. Lea, J.M. Lough, and G.B. Shimmield. 2001. Variability in the El Niño Southern Oscillation through a glacial-interglacial cycle. *Science* 291: 1511–1517.

Visser, K., R. Thunell, and L. Stott. 2003. Magnitude and timing of temperature change in the Indo-Pacific warm pool during deglaciation. *Nature* 421: 152–155.

Vuille, M. 1999. Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the Southern Oscillation. *International Journal of Climatology* 19: 1579–1600.

Webster, P.J. 1982. Seasonality in the local and remote response to sea surface temperature anomalies. *Journal of Atmospheric Science* 39: 41–52.

Webster, P.J. 1994. The role of hydrological processes in ocean-atmosphere interactions. *Reviews of Geophysics* 32: 427–476.

Yan, X.-H., C.-R. Ho, Q., Zheng, and V. Klemas. 1992. Temperature and size variabilities of the Western Pacific Warm Pool. *Science* 258: 1643–1645.